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CORRELATIONS BETWEEN BENCH-SCALE TEST AND ROOM CORNER TEST BASED ON A FLAME SPREAD MODELING

INTERPRETATION OF SMALL AND INTERMEDIATE SCALE FIRE TESTING

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ABSTRACT

A framework and indices to classify fire hazard of lining materials directly using row data from bench scale test are developed by the analysis of the qualitative and asymptotic behavior of concurrent flame spread models. The proposed index uses total heat release rate, time to ignition and time to burnout. Through comparative studies, this method has been found to lead to a reasonable correlation between the results of the Cone Calorimeter and the ISO9705 Room Corner Test.

***Keywords:** Cone Calorimeter, ISO 9705 Room Corner Test, flame spread, heat release rate, flashover.*

INTRODUCTION

Upward flame spread along a wall lining and horizontal flame development beneath a combustible ceiling is very often a direct trigger for the occurrence of flashover. Although the fear of concurrent flame spread should have been recognized from the dawn of the civilization, development and application to practice of Fire Safety Engineering(FSE) concepts and tools for lining materials is still far behind that in the smoke control and the structural fire safety. This is probably because of the complexity of the phenomena relevant to the fire safety of interior linings. Because of such difficulty in the engineering approach, most of the conventional regulations and tests on lining materials do not seem to have clear relevance with real fires. Moreover, comparative studies on standard reaction-to-fire tests in European countries during the 1960's revealed notable inconsistency in the then effective regulatory test methods[1]. Such inconsistency raised a doubt if the conventional classification properly represents the hazard of lining materials in real fires.

On the other hand, modeling of concurrent flame spread is probably one of the research topics in fire safety on which the progress of scientific understanding have been the most pronounced during the last two decades. Concurrent flame spread attracted combustion scientists relatively early, and the theoretical paradigm for its mathematical formulation was established before the 1980s[e.g.2, 3, 4, 5]. Most of the early works on flame spread, conducted within the combustion science rather than fire research, dealt with simple materials, laminar flow conditions and idealized configurations with few exceptions[6]. Modeling of flame spread in the fire safety engineering since around the 1980s has focused the treatment of turbulence, development of simulation method, reformulation using material properties measurable with practical testing apparatus as input, and the derivation of evaluation concepts for fire safety. These efforts have enabled prediction of concurrent flame spread for limited types of lining materials and the evaluation of the asymptotic behavior of fire development. These research efforts have been reflected in the development of performance-oriented reaction-to-fire tests by the ISO/TC92/SC1(reaction-to-fire). However, the complexity of the lining fires still seems to prevent practitioners such as building regulators, architects and material producers to introduce these research results into practice.

Most of the flame spread models in fire are based on a concept of ignition and flame spread as a result of inert heating of the solid to an ignition temperature(Figure 1). These models could be divided into two types; analytical and numerical models. Analytical models[e.g.7, 8, 9,10] generally introduce simplifications and assumptions whereas numerical ones[e.g.11,12] generally try to divide the combustible surface into finite difference grids and calculate the surface temperature of each grid. Numerical approach can deal with the precise distribution of the flame heat transfer and do not necessarily introduce any simplification. The benefit of the analytical approach is the ease to predict asymptotic and global behavior of the flame spread, e.g. autonomous flame extinction and the divergence of the solution. Another profit of analytical approach compared with numerical one in the light of practice, is probably that numerical models generally need such elementary properties of materials as thermal conductivity, density, specific heat and heat of combustion, which need to be measured individually and can be difficult for practical building materials.

NEEDS OF MODELING BASIS FOR MATERIAL CLASSIFICATION

Large scale and intermediate scale experiments on wall fires were conducted for the fire safety design of the wooden lining of the main theater of Japan's recently completed New National Theater. Since the design chosen by an international competition in 1986 proposed wooden lining and was against the Building Standard Law, Japan's Ministry of Construction(MoC) organized a project for its fire safety design[13]. Thickness, surface finish and other design features of the wooden wall lining was finally determined to localize the wall burning to less than three times the height of the pilot flame above the first ignited package. Although this project was useful to promote research on the combustible lining and flame spread in Japan, it is obvious that such investigations were possible only because it was a very large construction project.

In the application of engineering fire prediction to the practical fire safety design of interior linings, there are however at least two types of difficulties. First difficulty relates to the considerable sensitivity of the growth of a compartment fire to the fire source and other initial and boundary conditions. In spite of the importance of such conditions for fire growth, it is generally difficult to predict these conditions since they may change almost everyday or according to occupants. Such difficulty should be more pronounced as the room becomes smaller, because the smoke layer temperature and the interactions of radiation heat transfer tend to be augmented in small enclosures although these conditions are the dominating elements for the growth of a room fire. The another difficulty relates to the limitation in the man power and funds available for the design of interior linings in "common buildings". Despite such complexity in the prediction of lining fires, time, man power and funding allowance for the interior design of a common building is generally not enough to run mathematical models on different fire scenarios.

For the fire safety design of "common buildings", classification is believed to be still a most functional way for lining materials; the central problem for establishing a classification of materials within performance-based code system will be the harmonization between the FSE concepts and the grading system. Originally some of the currently available analytical flame spread models intended to use data from heat release tests such as the ISO5660 Cone Calorimeter as the input[14,15], and have potential capability for the application to the classification. Several works in the 1990s have tried to explain the results of the ISO 9705 Room Corner Test, a full scale test on lining fires, from the asymptotic flame spread behavior predicted by analytical models with the data from the ISO 5660 and other bench-scale tests.

Figure 2(a) is a graphical representation[10] of the asymptotic behaviors of the flame spread predicted from a simple analytical equation for concurrent flame spread first derived by Saito, Quintiere and Williams(the SQW equation, see equation(2))[8] and solved analytically by Thomas and Karlsson[9]. The SQW equation and its variations essentially represent flame spread velocity by the distance between the flame front and the pyrolysis front divided by the characteristic time to ignition, i.e. $V_p = (x_f - x_p)/\tau$. This formulation assumes a uniform flame heating between the flame front and the pyrolysis front and the simultaneous ignition over this area after the characteristic ignition time τ. τ is taken as constant in a stationary flame spread and can be represented by the time to ignition under the flame heat flux level. The SQW equation also employs a linearized flame length approximation, i.e. $x_f = L_f = KQ$ where Q is the total heat release rate per unit width of the pyrolysis zone, whilst experiments suggest a weaker power dependence, e.g. $x_f = L_f \propto Q^{2/3}$, for upward flame spread[8]. From experimental flame length correlations, K is believed to be around 0.01 - 0.02 for a [10^{-1}] - [10^{1}] m tall flame. The SQW equation has been generalized to incorporate the burnout effect[16], and the power dependence of the flame length[17,18]. While these improvements generally tend to make an analytical treatment rather difficult, the present paper tries to use only analytical treatment. The solution in Figure 2(a) assumes further a charring material, whose time history of heat release rate is represented by an exponential decay function, $q(t) = q_{max} \exp(-t/t_b)$. The solution can be divided into the following three categories according to its asymptotic behavior. Flame spreading velocity diverges in the region I, is accelerated at the beginning but is gradually decelerated and finally diminishes in the region II. Flame spread is decelerated from the beginning and will die out in the region III. Lining materials falling into the region I is believed to cause flashover, and those falling into the region II may cause flashover in a small enclosure compared with the fire source. A room fire should not reach flashover with any lining material in the region III, unless the fire source is large enough. For a heat release rate represented by a rectangular function of time, $q(t) = q_{max} \{1 - U(t - t_b)\}$, it has been found that the qualitative behavior of the solution can be divided into only two categories as seen in Figure 2(b)[16]. In this figure, the acceleration/deceleration criterion, $\tau/t_b = Kq_{max} - 1$, also stands for the divergence/convergence criterion. Through a different analysis, Quintiere derived an acceleration/deceleration criterion for the local heat release rate represented by a rectangular function[19]. This criterion is essentially equivalent with the acceleration/ deceleration boundary in Figure 2(b). He further demonstrated that his criterion can predict whether flashover occur in the first ten minutes in the ISO 9705 Room Corner test.

There are some criticisms against this approach from practitioners; use of not highly reproducible material properties, possible influence of subjective judgment in the approximation of the heat release rate by a simple function and the use of a small specimen to obtain the input data have been pointed out. A safer side approximation of the test data may resolve the first two criticism, but it may spoil the benefit of the prediction-based classification. The second criticism is rather directed to the use of bench scale tests for the evaluation of a large building product. Certainly complicated surface treatment, ribs, cavities and other construction details may not be represented in a 10 cm square specimen to be used for the Cone Calorimeter. Probably those lining materials featuring such complicated construction details need essentially an intermediate or large scale test. Also the basic assumption for the SQW equation has been found to be valid for only limited conditions[16,20], and there is some theoretical doubt in the validity of the analytical solution if it is far from the steady state. However, as long as the analytical approach is applied only for the evaluation of asymptotic flame spread behaviors, this approach should still be effective as there is no direct need to use its solution in such a qualitative evaluation.

CLASSIFICATION OF THE FLAME SPREAD BEHAVIOR

An attempt has been made to resolve such difficulty of the analytical approach. In order to derive a rational classification using row test data, analysis has been made on the generalized SQW equation:

$$V_p(t) = (x_f - x_p)/\tau = [K[Q_o(t)\{1 - U(t - t_b)\} + x_{po}q(t) + \int_0^t q(t-\xi)V_p(\xi)d\xi] + \{\int_0^{t-t_b} V_p(\xi)d\xi + x_{po}\}U(t - t_b) - \{x_{po} + \int_0^t V_p(\xi)d\xi\}]/\tau \quad (1)$$

The generalized SQW equation is a generalization of the SQW equation to incorporate the burnout effect[16]. For $t<t_b$, equation(1) can be simplified into the original SQW equation as

$$V_p(t) = [K[Q_o(t) + x_{po}q(t) + \int_0^t q(t-\xi)V_p(\xi)d\xi] - \{x_{po} + \int_0^t V_p(\xi)d\xi\}]/\tau$$
$$= [K\,Q_o(t) + x_{po}\{K\,q(t) - 1\} + \int_0^t \{K\,q(t-\xi) - 1\}V_p(\xi)d\xi]/\tau \quad (2)$$

Once the fire source is removed or extinguished, the fire source term $Q_o(t)$ disappears and equation(2) further becomes

$$V_p(t) = [\,x_{po}\{K\,q(t) - 1\} + \int_0^t \{K\,q(t-\xi) - 1\}V_p(\xi)d\xi]/\tau \quad (3)$$

Flame spread is sustained only when $V_p(t)>0$; equation(3) suggests that if $Kq(t) \geqq 1$ the flame spread can be sustained and if $Kq_{max} <1$ the flame spread should be terminated after the removal of the fire source. A "lining material that may ignite in fire but cannot sustain flame spread without the fire source" has a clear implication for fire safety, and this condition can be identified by judging if its heat release rate data satisfies $Kq_{max} <1$.

One deficit of $Kq_{max} <1$ for practical fire safety assessment is perhaps the use of the peak heat release rate, q_{max}, which, according to testing practice, is believed not to be very reproducible for its high sensitivity to the sampling interval and other reasons. Taking burnout into account, the following condition, weaker than $Kq_{max} <1$,

$$\int_0^{t_b} Kq(\xi)\,d\xi\,/\,t_b < 1 \quad (4)$$

is likely to assure a similar criterion for practical lining materials for the sustainability of flame spread. Equation(4) needs determination of burnout time,$t>t_b$, and total heat release rate, $\int_0^{t_b} q(\xi)d\xi$, both of which are less sensitive to measurement apparatus and protocol than q_{max} and are more reproducible than q_{max}. Effectiveness of this criterion can be demonstrated as follows.

For $t>t_b$, equation(1) yields

$$V_p(t) = \int_{t-t_b}^{t} \{Kq(t-\xi) - 1\}\,V_p(\xi)d\xi\,/\,\tau = \int_0^{t_b} \{Kq(\xi) - 1\}\,V_p(t-\xi)d\xi\,/\,\tau \quad (5)$$

Even if the flame spread velocity is positive, flame spread will be gradually decelerated and finally die out if $dV_p(t)/dt<0$. The condition for $dV_p(t)/dt<0$ can be obtained by taking the limit for a stationary flame spread from equation(5). Assuming $V_p(t)=constant$, equation(5) yields

$$\int_0^{t_b} Kq(\xi)d\xi\,/\,t_b - 1 = \tau\,/\,t_b \quad (6)$$

This condition is the divide between the accelerated and the decelerated modes of flame spread, and if the left hand side of equation(6) is smaller than the right hand side, τ / t_b, the flame spread is believed to be always decelerated. If furthermore the left hand side of equation(6) is negative, namely $\int_0^{t_b} Kq(\xi)\, d\xi / t_b < 1$, equation(5) suggests that positive value of V_p can be achieved only when $q(t)$ is an increasing function of time with its peak just before the burnout large enough to compensate the decrease of flame spread velocity with time. Obviously such functional form of $q(t)$ should be hardly consistent with equation(4) which specifies an upper limit of the total heat release rate. In various practical combustible lining materials, charring materials have normally the peak heat release rate slightly after the ignition, and there is virtually no lining material that has a significant peak at the end of surface burning while heat release rate of some noncharring materials such as PMMA is represented by a weakly increasing function of time. From these discussions, a lining material satisfying $\int_0^{t_b} Kq(\xi)\, d\xi / t_b < 1$ is believed to be unable to sustain flame spread once the surface burning is isolated from fire source by its removal or burnout of the surface burning. In that sense, this condition gives a strong limitation for the flame spread, and materials satisfying this condition can be referred to as "strongly self-extinguishable" materials.

Another characterization of burning behavior can be introduced for those materials that may sustain flame spread but cannot cause any accelerated flame spread. From equation(6), this condition can be represented as

$$\int_0^{t_b} Kq(\xi) d\xi / t_b - 1 < \tau / t_b \qquad (7)$$

Although this condition allows some larger fire development than the previous criteria, fire is expected to extinguish automatically, and those materials satisfying equation(7) may be referred to as "weakly self-extinguishable" materials.

The strongly and weakly self-extinguishable materials can be illustrated graphically as seen in Figure 3. The first term of the left hand side of equation(6) is equivalent to Kq_{max} for those materials whose dynamic heat release rate is represented either by an exponential or a rectangular function. The equation(6) is equivalent to the criticality, $\tau / t_b = Kq_{max} - 1$, in Figure 2 for these simple analytical solutions if, for an exponential function, the time constant representing the decay is used for t_b. In that sense, Figure 3 is a generalization of the Figures 2(a) and (b). Also, for heat release rate represented as a rectangular function, equation(6) becomes equivalent with the criteria that Quintiere[19] has derived for the classification of lining materials in terms of the time to flashover. It is important that all material properties included in the critical conditions for both the strongly and weakly extinguishable materials can be obtained directly with a material test to measure dynamic heat release rate such as the Cone Calorimeter, total heat release rate, time to ignition and the burnout time.

CORRELATION BETWEEN CONE CALORIMETER AND ROOM CORNER TEST

Various lining materials were tested against the Cone Calorimeter and the ISO 9705 Room Corner Test within the recently completed MoC R & D program on fire test methods. Table 1 is a summary of the specimens, material description and main results of the Cone Calorimeter(50kW/m2) and the ISO 9705 Room Corner Test. Although the number of materials was limited, the tested materials cover wide range of fire performance from *noncombustible materials* to those not rated as *fire protective materials* in the Building Standard Law. $K=0.02$ was assumed experimental flame height correlations on the similar range of flame height from the ignition source with the ISO 9705 Room Corner Test. Since time to burnout was not easy to identify visually for a few materials, the time to the heat release rate decaying to $20kW/m^2$ was defined as the time to burnout. This definition seemed to be consistent with visual definition for most of specimens with which the visual identification of burnout was easy. For the calculation of t_b, similar definition, q=, $20kW/m^2$ was used for the identification of the initiation of flaming. This simple definition led to minor difference with the visual definition of time to ignition as seen in Table 4. Classifying the ISO 9705 Room Corner Test results into four grades according to the time to flashover, i.e. no flashover, flashover between 10 and 20 minutes, flashover between 5 and 10 minutes and flashover before 5 minutes, the results from the Cone Calorimeter and the ISO 9705 Room Corner Test are correlated, according to the discussion in the previous section, as shown in Figure 4.

Table 1 also summarizes F values, a dimensionless index defined as

$$F = \tau / \{ \int_0^{t_b} Kq(\xi) d\xi - t_b \} \tag{8}$$

for each specimen. F is negative for strongly self-extinguishable materials, and larger than unity for weakly self-extinguishable materials. Table 4 suggests a promising prospect that F could be an index for practical prediction of the range of time to flashover at the ISO 9705 Room Corner Test; for $0 < F < 0.15$, flashover is likely to occur in 5 minutes from ignition, for $0.15 < F < 0.44$, flashover may occur between 5 and 10 minutes. Although clear flashover did not occur with the rest of F value range, unsustained flame projection from the doorway was observed for materials 7A0 and 8B with which average F value was between 1.1～1.8. Especially peak heat release rate for 7A0 at the ISO 9705 Room Corner Test exceeded 1000kW. If these are to be eliminated, $F > 2$ could be a condition for flashover not to occur at the ISO 9705 Room Corner Test. Also no flashover was observed with the two materials with $F < 0$. Use of K value still smaller than 0.02 may lead to a better correlation between the Cone Calorimeter and the ISO9705 Room Corner Test.

CONCLUDING REMARKS

As long as the ISO 9705 Room Corner Test is used as the reference for the fire safety assessment of lining materials, the analytical approach has a promising prospect to serve as a practical tool to classify the lining materials. The 2.4m x 3.6m room of the ISO9705 Room Corner Test represents a minimum room size in buildings, and the development of a lining fire should be faster than in a larger and commoner room. The practically sole domination of the results of the Room Corner Test by the concurrent flame spread may be partly because of the use of a very small enclosure in the Room Corner Test. Role of the downward flame spread along the enclosure boundaries can become more important in a larger compartment. Development of mathematical room fire models[e.g.21,22] is believed to be important for the better understanding of fire behavior in larger compartments.

TERMINOLOGY

$U(t)$: Heaviside's unit function
q :heat release rate per unit area
t : time
L_f : flame length
x_p : location of pyrolysis front
Q : heat release rate per unit width
Q_o : heat release rate of the ignition source
V_p : flame spread velocity
K : constant(L_f/Q)
t_b : time to burnout
x_f : location of flame front
x_{po} : pilot flame height
τ :characteristic time to ignition

References

1. Emmons,H.W.: Fire Research Abstracts and Reviews 10, No.2, 1968.

2. de Ris, J.: Spread of a Laminar Diffusion Flame, Proceedings of the Twelfth Symposium (International) on Combustion, 1968.

3. Hirano, T., Noreikis, S.E., and Waterman, T.E.: Postulations of Flame Spread Mechanisms, Combustion and Flame, 22, p.353, 1974.

4. Fernandez-Pello, A.C.: Theoretical Model for the Upward Laminar Spread of Flames over Vertical Fuel Surfaces, Combustion and Flame, 31, p.135, 1978.

5. Fernandez-Pello,A.C., and Hirano, T.: Controlling Mechanism of Flame Spread, Combustion Science and Technology, 32, p1, 1983.

6. Orloff, L., de Ris,J., and Markstein,G.H.: Upward Turbulent Flame Spread and Burning of Fuel Surface, Proceedings of the Fifteenth Symposium (International) on Combustion, 1974.

7. Hasemi,Y.: Thermal Modeling of Upward Flame Spread, Proceedings of the First International Symposium on Fire Safety Science, Gaithersburg, 1985.

8. Saito,K., Quintiere,J.G., and Williams,F.A.: Upward Turbulent Flame Spread and Burning of Fuel Surface, Proceedings of the First International Symposium on Fire Safety Science, Gaithersburg, 1985.

9. Thomas, P.H. and Karlsson, B.: On Upward Flame Spread, Department of Fire Safety Engineering, Lund University, 1991.

10. Baroudi, D. and Kokkala, M.A.: Analysis of Upward Flame Spread, VTT Publications 89, 1992.

11. Delichatsios, M.M., Mathews, M.K., and Delichatsios, M.A.: An Upward Fire Spread and Growth Simulation, Proceedings of the Third International Symposium on Fire Safety Science, Edinburgh, 1991.

12. Brehob, E.G., and Kulkarni, A.C.: A Nemerical Model for Upward Flame Spread under External Radiation, Annual Conference on Fire Research, Rockville, Md., 1993.

13. Anon.: Investigation Report for the Fire Safety Design of the New National Theater, Part I, Part II, Building Centre of Japan, 1987, 1988(in Japanese).

14. Kokkala,M.A., Thomas, P.H., and Karlsson, B.: Rate of Heat Release and Ignitability Indices for Surface Linings, Fire and Materials, 171, p209, 1993.

15. Ostman,B.A-L., and Nussbaum, R.M.: Correlation between Small-scale Rate of Heat Release and Full-scale Room Flashover for Surface Linings, Proceedings of the Second International Symposium on Fire Safety Science, Tokyo, 1988.

16. Hasemi, Y., and Yasui, N.: A Strategy to Develop Engineering Upward Flame Spread Evaluation Methodology Based on the Linearized Flame Height Approximation, Fire Science and Technology, Vol.15, No.1 & 2, 1995.

17. Grant,G., and Drysdale,D.D.: Numerical Modelling of Early Flame Spread in Warehouse Fires, Fire Safety Journal, Vol.24, p247 - 278, 1995.

18. Kokkala,M., Baroudi, D., and Parker,W.J.: Upward Flame Spread on Wooden Surface Products: Experiments and Numerical Modelling, Proceedings of the Fourth International Symposium on Fire Safety Science, p309 - 320, Melbourne, 1997.

19. Quintiere,J.G.: Fire Tests and Hazard Evaluation, UNCRD Proceedings Series No.7, Improved Firesafety Systems in Developing Countries, Tokyo, 1994.

20. Delichatsios,M.A., Delichatsios,M.M., Chen,Y., and Hasemi,Y.: Similarity Solutions and Applications to Turbulent Upward Flame Spread on Non-Charring Materials, Combustion and Flame, Vol.102, p357- 370, 1995.

21. Karlsson, K.:Modeling Fire Growth on Combustible Lining Materials in Enclosures, Lund University, 1992.

22. Cleary,T.G., and Quintiere,J.G.: A Framework for Utilizing Fire Property Test, Proceedings of the Third International Symposium on Fire Safety Science, Edinburgh, 1991.

Table 1 Materials and Summary Test Results of Cone Calorimeter and ISO9705 Room Corner Test

Specimen	Material	Time to ignition* (s)	Time to burnout* (s)	tb (s)	Time to ignition** τ(s)	Total heat release (kJ/m²)	$\int q''(t)dt/tb$ (kW/m²)	τ/tb (-)	F value (-)	ISO9705 Time to Flashover (min)	Class
7A0-1	Wall paper(PVC 300g/m²) on gypsumboard BSL rating QNC	14	58	44	16	2626	57.14	0.36	2.57	Unsustained flame projection at 10.3 min	1/2
7A0-2		12	58	46	9	2703	56.59	0.2	1.54		
7A0-3		14	56	42	10	2546	58.48	0.24	1.41		
7A1-1	Wall paper(PVC 500g/m²) on gypsumboard BSL rating FR	14	76	62	9	4814	76.34	0.15	0.28	11.1	2
7A1-2		10	70	60	9	4765	78.57	0.15	0.26		
7A1-3		10	70	60	7	4765	78.57	0.12	0.21		
7F1-1	Polyisocyanulate + gypsumboard BSL rating -	4	72	68	2	5228	76.09	0.03	0.06	0.73	4
7F1-2		22	74	52	2	3415	63.69	0.04	0.15		
7F1-3		18	72	54	2	4057	72.48	0.04	0.09		
7G-1	FR plywood BSL rating FR	16	600	584	22	50022	85.59	0.04	0.06	4.5	4
7G-2		20	600	580	19	58443	100.59	0.03	0.03		
7G-3		24	600	576	24	47393	82.21	0.04	0.06		
7Q-1	Soft fiberboard BSL rating -	11	467	456	8	32453	71.14	0.02	0.05	not conducted for safety reason	4
7Q-2		9	502	493	7	33712	68.37	0.01	0.03		
7Q-3		9	506	497	7	34410	69.22	0.01	0.03		
8A-1	Wall paper(FR cloth 700g/m²) on gypsumboard BSL rating FR	34	176	142	36	5960	40.56	0.25	-1.32	NO FO	1
8A-2		36	184	148	40	6760	43.88	0.27	-2.25		
8A-3		36	178	142	35	5644	38.28	0.25	-1.09		
8B-1	Wall paper(FR cloth 300g/m²) on gypsumboard BSL rating QNC	27	109	82	23	5648	67.37	0.28	0.8	Unsustained flame projection at 10.3 min	1/2
8B-2		27	111	84	24	5255	60.46	0.29	1.38		
8B-3		27	105	78	24	5020	62.12	0.31	1.29		
8C-1	Emulsion paint +gypsumboard BSL rating QNC	52	72	20	49	2233	100.35	2.45	2.43	NO FO	1
8C-2		56	74	18	53	2062	108.06	2.94	2.53		
8C-3		66	84	18	64	1961	100.78	3.56	3.49		
8D-1	Acrylic paint+gypsumboard BSL rating QNC	31	67	36	26	3186	83.89	0.72	1.06	NO FO	1
8D-2		35	71	36	31	3009	79.75	0.86	1.43		
8D-3		33	69	36	30	2974	77.36	0.83	1.51		
8E-1	Emulsion paint (70g/m²)+gypsumboard BSL rating NC	38	60	22	35	2652	113	1.59	1.26	NO FO	1
8E-2		44	62	18	41	2456	133.67	2.28	1.37		
8E-3		48	66	18	45	2423	128.11	2.5	1.6		
8F-1	Emulsion paint (111g/m²)+gypsumboard BSL rating NC	47	99	52	41	5606	104.35	0.79	0.72	NO FO	1
8F-2		43	93	50	36	5164	98.6	0.72	0.74		
8F-3		45	95	50	39	5415	104.96	0.78	0.71		
8K-1	Wall paper (PVC 300g/m²) +gypsumboard BSL rating QNC	38	64	26	14	1479	40.5	0.54	-2.84	NO FO	1
8K-2		6	94	88	15	2959	32.9	0.17	-0.5		
8K-3		10	52	42	16	2167	48.5	0.38	-12.67		
10C-1	FR plywood	124	600	476	124	32336	67.49	0.26	0.74		
10C-2		132	600	468	132	28604	60.5	0.28	1.33		
10C-3		136	600	464	136	30736	65.37	0.29	0.94		
10D-1	Composite: Aluminum +Polyethylene+Aluminum	220	664	444	220	47990	106.68	0.5	0.44	7.0	3
10D-2		216	756	540	210	70901	130.05	0.39	0.24		
10D-3		216	756	540	210	70901	130.05	0.39	0.24		

BSL rating: NC=*Noncombustible material*, QNC=*Quasi-noncombustible material*, FR=*Fire retardant material.*

* defined from heat release rate assuming $q''=20kW/m^2$ for the start and termination of flaming

** defined from visual observation according to ISO5660 and Cone Calorimeter protocols.

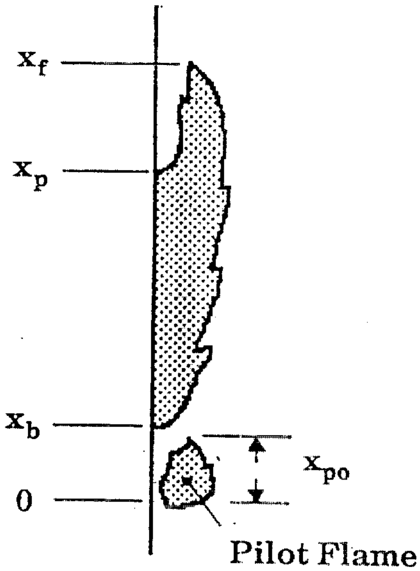
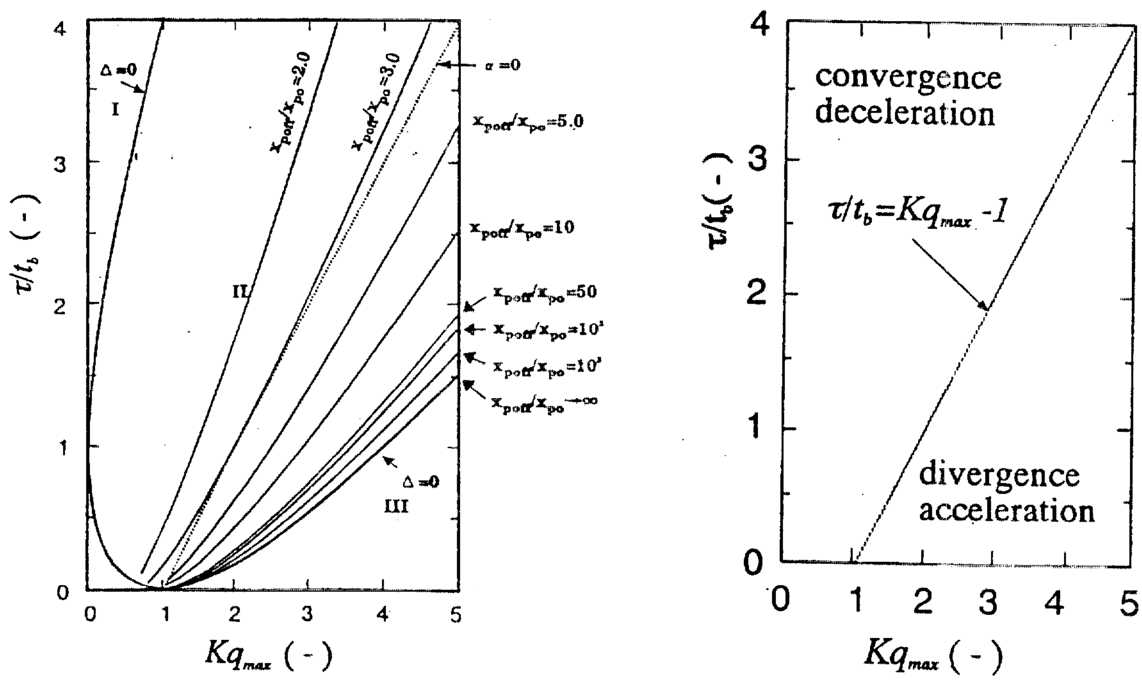


Figure 1 Wall Flame Spread, Schematic Diagram



(a) Charring materials, sustained pilot flame $q(t)= q_{max}\, exp(-t/t_b)$

(b) Non-charrig materials $q(t)= q_{max}\{1 - U(t - t_b)\}$

Figure 2 Asymptotic Behaviors of Concurrent Flame Spread

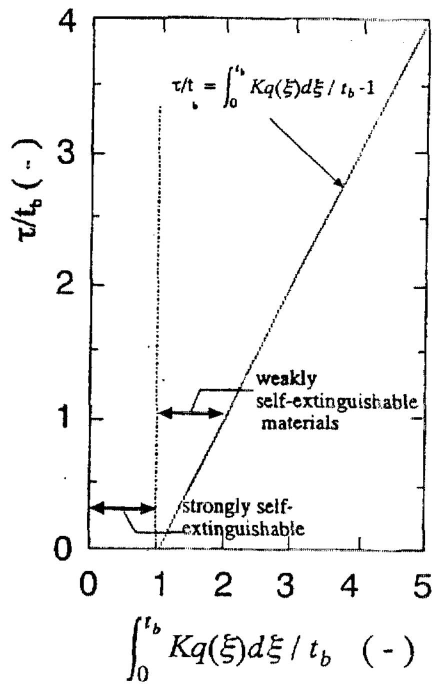


Figure 3 Classification of Asymptotic flame spread behaviors by row heat release data

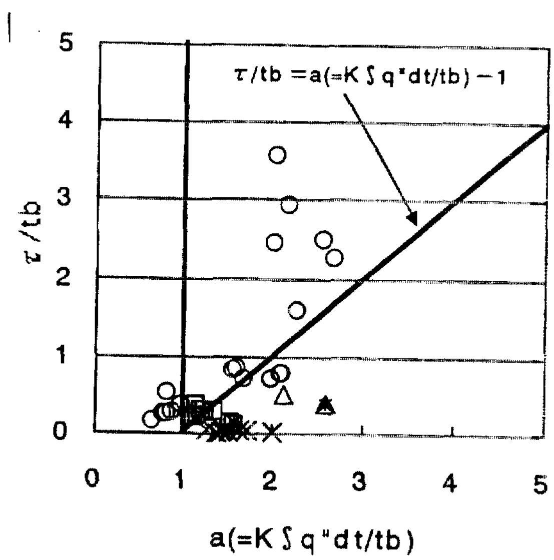


Figure 4 Correlation between the time to flashover in ISO9705 Room Corner Test and heat release characteristics at heat flux level 50kW/m² in the Cone Calorimeter